Hierarchical, High Fidelity Modeling and Simulation of Static and Dynamic Behaviour of Soil Structure Systems

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Outline

Introduction
   Motivation
   Real ESSI Simulator System

Seismic Motions
   Observations and Regional Models
   Stress Test Motions

Inelasticity and Energy Dissipation
   Energy Dissipation
   Probabilistic Inelastic Modeling

ESSI Modeling and Simulations
   Nuclear Power Plant Modeling and Simulation
   Small Modular Reactors Modeling and Simulation
   Liquefaction

Conclusion
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Motivation

Improve modeling and simulation for infrastructure objects

Use of high fidelity numerical models to analyze behavior of soil structure systems

Reduction of modeling uncertainty, ability to perform high(er) level of sophistication modeling and simulation

Accurately follow the flow of input and dissipation of energy in a soil structure system

Development of an expert, rational physics based, system for modeling and simulation
Hypothesis

- Interplay dynamic characteristics of the Dynamic Forcing / Earthquake, Soil/Rock and Structure in time domain, plays a decisive role in successes and failures

- Timing and spatial location of energy dissipation determines location and amount of damage

- If timing and spatial location of the energy dissipation can be controlled (directed), we could optimize soil structure system for
  - Safety and
  - Economy
Predictive Capabilities

- Prediction under Uncertainty: use of computational model to predict the state of SSI system under conditions for which the computational model has not been validated.

- Verification provides evidence that the model is solved correctly. Mathematics issue.

- Validation provides evidence that the correct model is solved. Physics issue.

- Modeling and parametric uncertainties are always present, need to be addressed

- Predictive capabilities with low Kolmogorov Complexity

- Goal: Predict and Inform and not (force) Fit
Modeling Uncertainty

- Simplified modeling: Features (important?) are neglected (6D ground motions, inelasticity)

- Modeling Uncertainty: unrealistic and unnecessary modeling simplifications

- Modeling simplifications are justifiable if one or two level higher sophistication model shows that features being simplified out are not important
Parametric Uncertainty: Material Stiffness

\[ E = (101.125 \times 19.3) \times N^{0.63} \]
Parametric Uncertainty: Material Properties

Field $\phi$

Lab $\phi$

Field $c_u$

Lab $c_u$
Realistic ESSI Modeling Uncertainties

- Seismic Motions: 6D, inclined, body and surface waves (translations, rotations); Incoherency
- Inelastic material: soil, rock, concrete, steel; Contacts, foundation–soil, dry, saturated slip–gap; Nonlinear buoyant forces; Isolators, Dissipators
- Uncertain loading and material
- Verification and Validation $\Rightarrow$ Predictions
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Real ESSI Simulator System

The Real ESSI, **Real**istic modeling and simulation of **Earthquakes**, **Soils**, **Structures** and their **Interaction**. Simulator is a software, hardware and documentation system for high fidelity, high performance, time domain, nonlinear/inelastic, deterministic or probabilistic, 3D, finite element modeling and simulation of:

- statics and dynamics of soil,
- statics and dynamics of rock,
- statics and dynamics of structures,
- statics of soil-structure systems, and
- dynamics of earthquake-soil-structure system interaction

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High Fidelity Modeling and Simulation
Real ESSI Simulator System

- Real ESSI System Components
  - Pre-processor (gmsh/gmESSI, X2ESSI, SASSI2ESSI)
  - Simulator (local, remote/cloud)
  - Post-Processor (Paraview, Python, Matlab)

- Real ESSI System availability:
  - Professional Practice and Educational Institutions: Amazon Web Services (AWS, economical!)
  - Government Agencies, National Labs and some Companies: Local/Remote

- Real ESSI Education and Training

System description and documentation at
http://real-essi.us/
Quality Assurance

- Full verification suit for each element, model, algorithm
- Certification process in progress for NQA-1 and ISO-90003-2014
High Fidelity (Parametric, Geometric and Algorithmic)
Example: Verification for Elastoplastic Algorithms
Comparison between forward and backward Euler algorithms.

Drucker-Prager Non-Associate Material with Backward Euler Algorithm

<table>
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<tr>
<th>ζ</th>
<th>0.05</th>
<th>0.10</th>
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<tbody>
<tr>
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<td>0.892</td>
<td>0.870</td>
<td>0.858</td>
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<tr>
<td>GCI</td>
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<td>0.33%</td>
<td>0.41%</td>
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<td>Result(Pa)</td>
<td>33816.496</td>
<td>36714.681</td>
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<td>Uncertain(Pa)</td>
<td>±77.673</td>
<td>±121.912</td>
<td>±156.082</td>
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<tr>
<td>Richardson(Pa)</td>
<td>33878.635</td>
<td>36812.210</td>
<td>38624.345</td>
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Drucker-Prager Non-Associate Material with Forward Euler Algorithm

<table>
<thead>
<tr>
<th>ζ</th>
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<td>0.08%</td>
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<td>33867.058</td>
<td>36790.815</td>
<td>38594.722</td>
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</table>
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3D (6D) Seismic Motions

- All (most) measured motions are full 3D (6D)
- One example of an almost 2D motion (LSST07, LSST12)

- 1D (?) - M 6.9 San Pablo, Guatemala EQ, 14Jun2017
Regional Geophysical Models

- High fidelity free field seismic motions on regional scale
- Knowledge of geology (deep and shallow) needed
- High Performance Computing using SW4 on CORI (LBNL)
- Collaboration with LLNL: Dr. Rodgers, Dr. Pitarka and Dr. Petersson
Regional Geophysical Models

Rodgers and Pitarka

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Regional Geophysical Models

USGS

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Example Regional Model

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Example Regional Model (Rodgers)
ESSI: 6D or 1D Seismic Motions

- Assume that a full 6D (3D) motions at the surface are only recorded in one horizontal direction
- From such recorded motions one can develop a vertically propagating shear wave in 1D
- Apply such vertically propagating shear wave to the same soil-structure system
6D Free Field Motions (closeup)
Observations and Regional Models

1D vs 3D Seismic Motions

- One component of motions (1D) from 3D
- Excellent fit

(DB: npp_model101_ff_quake.h5.feiooutput
Time: 0.77
Mesh
- (MP4)

(DB: npp_model101_ff_quake.h5.feiooutput
Time: 0.712
Mesh
- (MP4)

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High Fidelity Modeling and Simulation
6D vs 1D NPP ESSI Response Comparison

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High Fidelity Modeling and Simulation
<table>
<thead>
<tr>
<th>Introduction</th>
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<th>Inelasticity and Energy Dissipation</th>
<th>ESSI Modeling and Simulations</th>
<th>Conclusion</th>
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Conclusion

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High Fidelity Modeling and Simulation
Stress Testing SSI Systems

- Excite SSI system with a suite of seismic motions
- Simple sources, variation in strike and dip, P and S waves, surface waves (Rayleigh, Love, etc.)
- Stress test soil-structure system
- Try to "break" the system, shake-out strong and weak links
Stress Test Motions

Stress Test Source Signals

- Ricker

- Ormsby

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High Fidelity Modeling and Simulation
Layered and Dyke/Sill Models

- (a) Horizontal layers
- (b) Dyke/Sill intrusion

- Source locations matrix (point sources)
- Source strike and dip variation
- Magnitude variations
- Range of frequencies
Layered System, Displacement Traces

- Epicenter is 2500m away from the location of interest
- Source depth 850m (left) and 2500m (right)
- Different wave propagation path to the point of interest
- Surface waves quite pronounced
- Layered geology did not filter out surface waves

\[
z_s = 850m, \text{ dip} = 45^\circ
\]

\[
z_s = 2500m, \text{ dip} = 45^\circ
\]
### Stress Test Motions

**Layered System, Variable Source Depth**

(MP4)  

(MP4)
Dyke/Sill Intrusion, Variable Source Depth

- Lower amplitudes than with layered only model!
- Difference in body and surface wave arrivals
- Surface waves present, more complicated wave field

\[ z_s = 850 \text{m}, \text{dip}=45^\circ \]
\[ z_s = 2500 \text{m}, \text{dip}=45^\circ \]
Dyke/S sill Intrusion, Variable Source Depth

(MP4)

(MP4)
Dyke/Sill as Seismic Energy Sink

- Dyke/Sill (right Fig), made of stiff rock, is an energy sink, as well as energy reflector.
- Variable wave lengths behave differently, depending on dyke/sill geometry and location.
Energy Dissipation

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Energy Input and Dissipation

Energy input, dynamic forcing

Mechanical dissipation outside SSI domain:
- SSI system oscillation radiation
- Reflected wave radiation

Mechanical dissipation/conversion inside SSI domain:
- Inelasticity of soil and contact zone
- Inelasticity/damage of structure and foundation
- Viscous coupling of porous solid and pore fluids (soil)
- Viscous coupling of structures with fluids

Numerical energy dissipation/production
Energy Dissipation

Fully Coupled Formulation, \( u-p-U \)

\[
\begin{bmatrix}
(M_s)_{KijL} & 0 & 0 \\
0 & 0 & 0 \\
0 & 0 & (M_f)_{KijL}
\end{bmatrix}
\begin{bmatrix}
\ddot{u}_{Lj} \\
\ddot{p}_N \\
\ddot{U}_{Lj}
\end{bmatrix}
+ \begin{bmatrix}
(C_1)_{KijL} & 0 & -(C_2)_{KijL} \\
0 & 0 & 0 \\
-(C_2)_{LjiK} & 0 & (C_3)_{KijL}
\end{bmatrix}
\begin{bmatrix}
\dot{u}_{Lj} \\
\dot{p}_N \\
\dot{U}_{Lj}
\end{bmatrix}
+ \begin{bmatrix}
(K_{EP})_{KijL} & -(G_1)_{KiM} & 0 \\
-(G_1)_{LjM} & -P_{MN} & -(G_2)_{LjM} \\
0 & -(G_2)_{KiL} & 0
\end{bmatrix}
\begin{bmatrix}
\ddot{u}_{Lj} \\
\ddot{p}_M \\
\ddot{U}_{Lj}
\end{bmatrix}
= \begin{bmatrix}
-f_{Ki}^{\text{solid}} \\
0 \\
-f_{Ki}^{\text{fluid}}
\end{bmatrix}
\]
Energy Dissipation

Fully Coupled Formulation, $u$-$p$-$U$

\[
(M_s)_{KijL} = \int_{\Omega} H_K^u (1 - n) \rho_s \delta_{ij} H_L^u d\Omega \\
(M_f)_{KijL} = \int_{\Omega} H_K^u n \rho_f \delta_{ij} H_L^u d\Omega \\
(C_1)_{KijL} = \int_{\Omega} H_K^u n^2 k_{ij}^{-1} H_L^u d\Omega \\
(C_2)_{KijL} = \int_{\Omega} H_K^u n^2 k_{ij}^{-1} H_L^u d\Omega \\
(C_3)_{KijL} = \int_{\Omega} H_K^u n^2 k_{ij}^{-1} H_L^u d\Omega \\
(K^{EP})_{KijL} = \int_{\Omega} \int_H K_{K,m}^u D_{imjn}^l H_{L,n}^u d\Omega \\
(G_1)_{KiM} = \int_{\Omega} H_{K,i}^u (\alpha - n) H_M^p d\Omega \\
(G_2)_{KiM} = \int_{\Omega} n H_{K,i}^u H_M^p d\Omega \\
(P_{NM}) = \int_{\Omega} H_M^p \frac{1}{Q} H_M^p d\Omega
\]
Energy Dissipation Control Mechanisms

Numerical  Viscous  Plasticity
Energy Dissipation Control

![Graph showing energy dissipation control with various energy components over time](image)

- Kinetic Energy
- Strain Energy
- Plastic Free Energy
- Plastic Dissipation
- Viscous Damping
- Numerical Damping
- Input Work

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Energy Dissipation

**Incremental Plastic Work:**

\[ dW_p = \sigma_{ij} d\varepsilon_{ij}^{pl} \]

- Negative incremental energy dissipation
- Plastic work is NOT plastic dissipation

---

*From a paper on *Soil Dynamics and Earthquake Engineering* (2011)*
Negative Incremental Energy Dissipation!

Direct violation of the second law of thermodynamics

600 papers since 1990 (!?!?) repeat this error

Important form of energy missing: Plastic Free Energy

First described by Taylor and Quinney in 1925 and then 1934!

Plastic Work vs. Plastic Energy Dissipation
Energy Dissipation on Material Level

Single elastic-plastic element under cyclic shear loading
Difference between plastic work and dissipation
Plastic work can decrease, dissipation always increases
Energy Dissipation for Soil Structure Systems

Examples of energy dissipation for buildings (nuclear power plants and small modular reactors) are given in section on ESSI modeling and simulation.
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Conclusion
Parametric Uncertainty: Material and Loads

- Significant uncertainty in material and loads
- Propagate uncertainties in space and time

Transformation of SPT $N$-value: 1-D Young’s modulus, $E$ (cf. Phoon and Kulhawy (1999B))
Stochastic Elastic-Plastic Finite Element Method (SEPFEM)

Material uncertainty expanded along stochastic shape functions:
\[ D(x, t, \theta) = \sum_{i=0}^{P_d} r_i(x, t) \ast \Phi_i[\{\xi_1, ..., \xi_m\}] \]

Loading uncertainty expanded along stochastic shape functions:
\[ f(x, t, \theta) = \sum_{i=0}^{P_f} f_i(x, t) \ast \zeta_i[\{\xi_{m+1}, ..., \xi_f\}] \]

Displacement expanded along stochastic shape functions:
\[ u(x, t, \theta) = \sum_{i=0}^{P_u} u_i(x, t) \ast \Psi_i[\{\xi_1, ..., \xi_m, \xi_{m+1}, ..., \xi_f\}] \]
### SEPFEM: Formulation

Stochastic system of equation resulting from Galerkin approach

\[
\begin{bmatrix}
\sum_{k=0}^{P_d} \langle \phi_k \psi_0 \psi_0 | K^{(k)} angle & \cdots & \sum_{k=0}^{P_d} \langle \phi_k \psi_P \psi_0 | K^{(k)} angle \\
\sum_{k=0}^{P_d} \langle \phi_k \psi_0 \psi_1 | K^{(k)} angle & \cdots & \sum_{k=0}^{P_d} \langle \phi_k \psi_P \psi_1 | K^{(k)} angle \\
\vdots & \cdots & \vdots \\
\sum_{k=0}^{P_d} \langle \phi_k \psi_0 \psi_P | K^{(k)} angle & \cdots & \sum_{k=0}^{M} \langle \phi_k \psi_P \psi_P | K^{(k)} angle
\end{bmatrix}
\begin{bmatrix}
u_{10} \\
\vdots \\
u_{N0} \\
\vdots \\
u_{1Pu} \\
\vdots \\
\nu_{NPu}
\end{bmatrix}
= \begin{bmatrix}
\sum_{i=0}^{P_f} f_i \langle \psi_0 \zeta_i > \\
\sum_{i=0}^{P_f} f_i \langle \psi_1 \zeta_i > \\
\sum_{i=0}^{P_f} f_i \langle \psi_2 \zeta_i > \\
\vdots \\
\sum_{i=0}^{P_f} f_i \langle \psi_{Pu} \zeta_i >
\end{bmatrix}
\]

<table>
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<th># KL terms material</th>
<th># KL terms load</th>
<th>PC order displacement</th>
<th>Total # terms per DoF</th>
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<tr>
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</table>
SEPFE M : Probabilistic Elastic-Plastic Modeling

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Probabilistic Inelastic Modeling

SEPFEM: Example in 1D

Stochastic Displacement from SEPFEM

Fragility Curve of Node number 1

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SEPFEM : Example in 3D

Stochastic Motion of an 8-node brick with Uncertain Young’s Modulus

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Conclusion
Modeling Sophistication Levels, Phased Modeling

- Level of sophistication chosen to reduce modeling uncertainty
- Verify code, solutions, methods, elements, material models
- Verify model components
- Model developed in phases (components) and verified
- Gradually building confidence in inelastic modeling
- Use such developed models to predict and inform, rather than force fit
Model Verification and Modeling Phases
Inelastic Modeling for NPP and Components

- Soil elastic-plastic
  - Dry, single phase
  - Unsaturated (partially saturated)
  - Fully saturated

- Contact, inelastic, soil/rock – foundation
  - Dry, single phase, Normal (hard and soft, gap open/close), Friction (nonlinear)
  - Fully saturated, suction and excess pressure (buoyant force)

- Structural inelasticity/damage
  - Nonlinear/inelastic 1D fiber beam
  - Nonlinear/inelastic 2D wall element
NPP Model

- Auxiliary Building
- Containment Building
- Foundation
- Damping Layers
- Contact
- Soil
- DRM Layer

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High Fidelity Modeling and Simulation
Structure Model

The nuclear power plant structure comprise of:

- Auxiliary building, $f_{aux}^1 = 8 \text{Hz}$
- Containment/Shield building, $f_{cont}^1 = 4 \text{Hz}$
- Concrete raft foundation: 3.5m thick

![Diagram of nuclear power plant structure with labels and dimensions]
Inelastic Soil and Inelastic Contact

- Shear velocity of soil \( V_s = 500\, m/s \)
- Undrained shear strength (Dickenson 1994)
  \[
  V_s[m/s] = 23(S_u[kPa])^{0.475}
  \]
- For \( V_s = 500\, m/s \) Undrained Strength \( S_u = 650\, kPa \) and Young’s Modulus of \( E = 1.3\, GPa \)
- von Mises, Armstrong Frederick kinematic hardening
  \( S_u = 650\, kPa \) at \( \gamma = 0.01\% ; h_a = 30\, MPa , c_r = 25 \)
- Soft contact (concrete-soil), gaping and nonlinear shear
Acc. Response, Top of Containment Building

- Elastic
- Inelastic

Time [s]

Frequency [Hz]

FFT $A_x [g]$

FFT $A_y [g]$

FFT $A_z [g]$
Nuclear Power Plant Modeling and Simulation

Acceleration Traces, Free Field

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Nuclear Power Plant Modeling and Simulation

Acceleration Traces, Elastic vs Inelastic
Elastic and Inelastic Response: Differences

Time: 10.67 [s]
Energy Dissipation in Large-Scale Model (NPP)
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Inelastic Modeling for Components

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  - Fully saturated, suction and excess pressure (buoyant force)

- Structural inelasticity/damage
  - Nonlinear/inelastic 1D fiber beam
  - Nonlinear/inelastic 2D wall element
## Soil Modeling Parameters

<table>
<thead>
<tr>
<th>Material parameters</th>
<th>Value</th>
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<tbody>
<tr>
<td>shear wave velocity [m/s]</td>
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<tr>
<td>Young’s modulus [GPa]</td>
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<td>Poisson ratio</td>
<td>0.25</td>
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<td>von Mises radius [kPa]</td>
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<td>linear hardening parameter [MPa]</td>
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<table>
<thead>
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<th>Contact parameters</th>
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<td>hardening rate [/m]</td>
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<td>maximum normal stiffness [N/m]</td>
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<td>tangential stiffness [N/m]</td>
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<td>tangential damping [N/(m/s)]</td>
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<table>
<thead>
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</tr>
<tr>
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</tr>
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<td>60%</td>
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![Stress-Strain Curve](image1)

![Penetration vs. Stiffness](image2)
Small Modular Reactors Modeling and Simulation

Representative points

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SMR: Inelastic ESSI Effects, Top Center

Jeremić et al.

High Fidelity Modeling and Simulation
SMR: ESSI Effects, Material Modeling

Material A: nonlinear, vM - AF

Material B: Bilinear

Jeremić et al.

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SMR: Accelerations Along Depth

Nonlinear site effects

SSI effects

Jeremić et al.

High Fidelity Modeling and Simulation
The PGA & PGD of SSI systems are (very) different from free field motions,
Material nonlinearity has significant effect on acceleration response.
Elastic and Inelastic Response: Differences

Time: 10.14 [s]

(MP4)

Jeremić et al.
High Fidelity Modeling and Simulation
Energy Dissipation for an SMR

Accumulated Plastic Dissipation Density (J/m3)

Incremental Plastic Dissipation Density (J/m3)

(MP4) Jeremić et al.

High Fidelity Modeling and Simulation
Buoyant Force Simulation

8 node solid brick (3 dofs)

8 node upU (7 dofs)

Coupled Contact

Displacements UZ
Solid/Structure-Fluid Interaction: gmFoam

- Mesh separation
  - integrated geometry model
  - FEM & FVM mesh conversion
  - handle discontinuous mesh

- Incorporate gmESSI

- Interface geometry extraction

- Interface class **SSFI** in RealESSI

RealESSI $\leftrightarrow$ SSFI $\leftrightarrow$ OpenFoam
Solid/Structure-Fluid Interaction, Example

(MP4)

Jeremić et al.

High Fidelity Modeling and Simulation
Outline

Introduction
  Motivation
  Real ESSI Simulator System

Seismic Motions
  Observations and Regional Models
  Stress Test Motions

Inelasticity and Energy Dissipation
  Energy Dissipation
  Probabilistic Inelastic Modeling

ESSI Modeling and Simulations
  Nuclear Power Plant Modeling and Simulation
  Small Modular Reactors Modeling and Simulation
  Liquefaction

Conclusion
Liquefaction

Saturated Soil

- For fully and partially saturated layers of loose to medium sand, with fines, silt, and with in-between layers of low permeability clay, liquefaction is likely

- Liquefaction can result in uniform and differential settlements!

- Liquefaction can also base isolate objects


- Piles in liquefied soil, pile pinning effects

  (Zhao Cheng and Boris Jeremic. Numerical Simulations of Piles in Liquefied Soils. Soil Dynamics and Earthquake Engineering, No. 29, pp 1405-1416, 2009.)
Liquefaction as Base Isolation, Model

Jeremić et al.

High Fidelity Modeling and Simulation
Liquefaction, Wave Propagation
Liquefaction, Excess Pore Pressure Ratio

Jeremić et al.
High Fidelity Modeling and Simulation
Liquefaction, Stress-Strain Response
Liquefaction

Pile in Liquefiable Soil, Model

Jeremić et al.

High Fidelity Modeling and Simulation
Liquefaction

Pile in Liquefiable Soil, Results

Jeremić et al.

High Fidelity Modeling and Simulation
Summary

- Numerical modeling to predict and inform, rather than fit
- Sophisticated inelastic/nonlinear modeling and simulations need to be done carefully and in phases
- Education and Training is the key!
- \url{http://real-essi.us/}
- Collaborators: Feng, Lacour, Han, Behbehani, Sinha, Wang, Pisanó, Abell, McCallen, McKenna, Petrone, Rodgers, Petersson, Pitarka
- Funding from and collaboration with the US-DOE, US-NRC, US-NSF, CNSC-CCSN, UN-IAEA, and Shimizu Corp. is greatly appreciated,